Introduction to Astrometry

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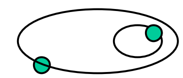
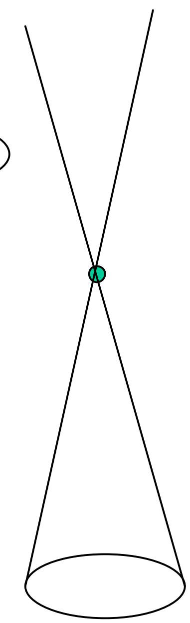
Interferometry Summer School

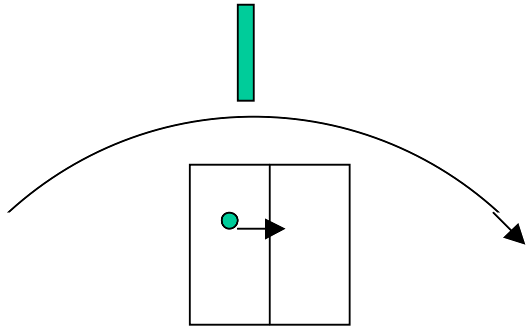
Science Objectives



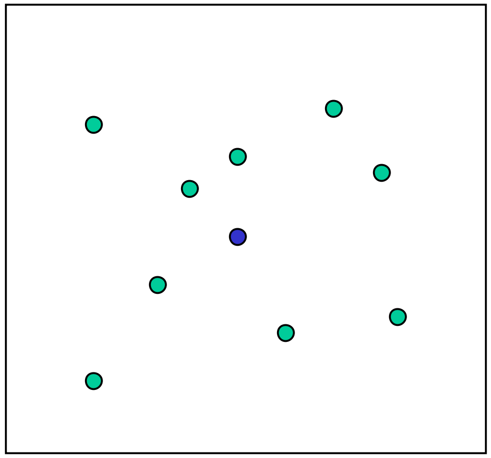


- Astrometry is the precise measurement of positions of stars (and other objects)
- At sufficiently high accuracy the stars are no longer stationary, they move
  - Presence of a planet orbiting the star
    - Mass of astrophysical objects
  - Annual parallax, cosmic distance scale
  - Gravitational lensing
  - Galactic rotation, dark matter

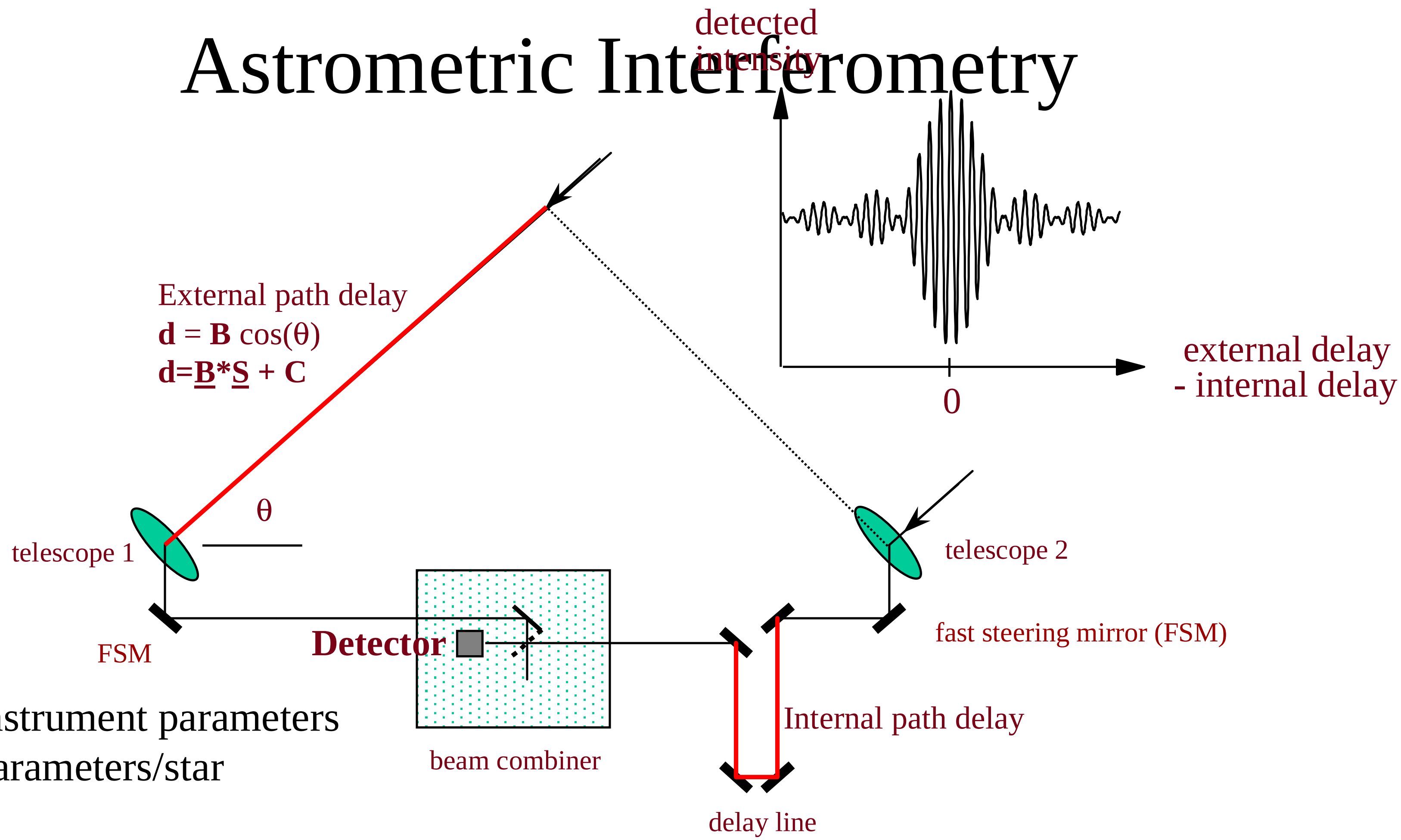
Historical Techniques



- Optical techniques
  - Global, transit telescope
  - Narrow field, imaging telescopes
    - Photography
    - CCD/photoelectric
- Radio techniques
  - VLBI



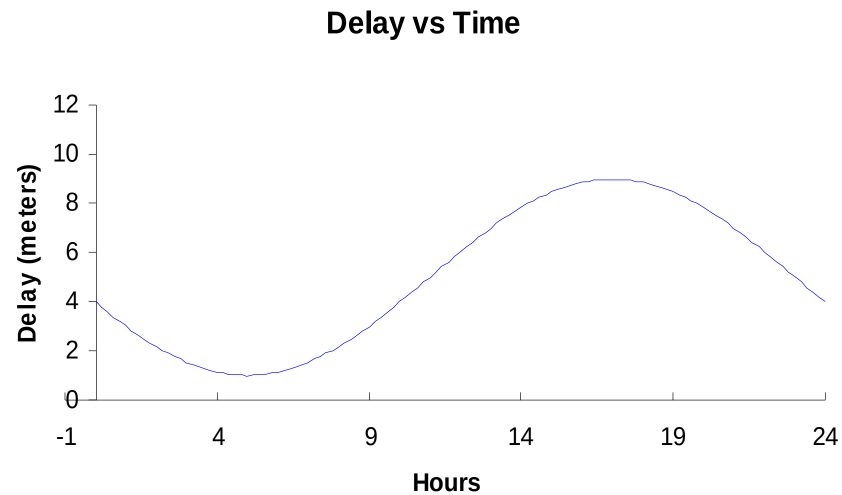
Astrometric Interferometry



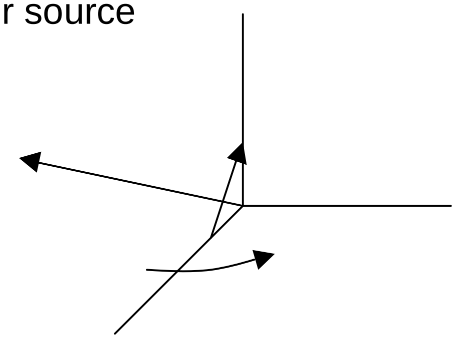
4 instrument parameters
2 parameters/star

The peak of the interference pattern occurs when the internal path delay equals the external path delay

Ground Astrometry



Baseline fixed to the Earth
Earth rotation rate very stable (if modeled)
Baseline orientation is known to ~100 uas (VLBI) ~mas (optical)
Turbulent atmosphere major error source



Delay vs time is characterized by
DC (dec, Bz)
Amplitude (Bx, By, amp)
phase (RA, Bx, By)
3 parameters measured
(4 stars, 12 measurement
8 stellar parameters, 4 instrument parameters)
Solve for baseline vector and star positions (except RA)

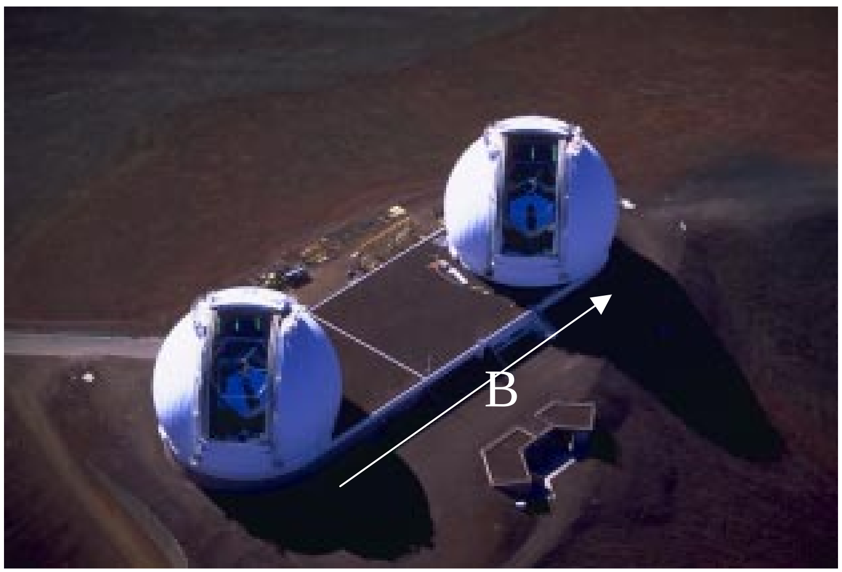
Metrology a Key Element of Astrometry

- While radio interferometer achieve high accuracy with baselines that are 1000's of km, an optical interferometer achieves similar accuracy by measuring the delay accurately
  - 1 mas, 30m baseline => δ delay = 150 nm (nanometer)
  - 10 uas, 100 m baseline => δ delay = 5 nm
  - 1 uas, 10m baseline => δ delay = 50 pm (picometer)
- The precise measurement of angles depends on the precise measurement of distance.

Delay=$\underline{S}$*$\underline{B}$+C, What's B?

The baseline is a vector joining the two telescopes.

If we need to define B at the nano to picometer level, what part of the Keck telescope is called one end of the baseline vector?



Center of the primary?
(secondary, tertiary?)

Pivot point of the telescope mount?
(Az and El do not intersect?)

A point on the "floor" directly below the az-el intersection?

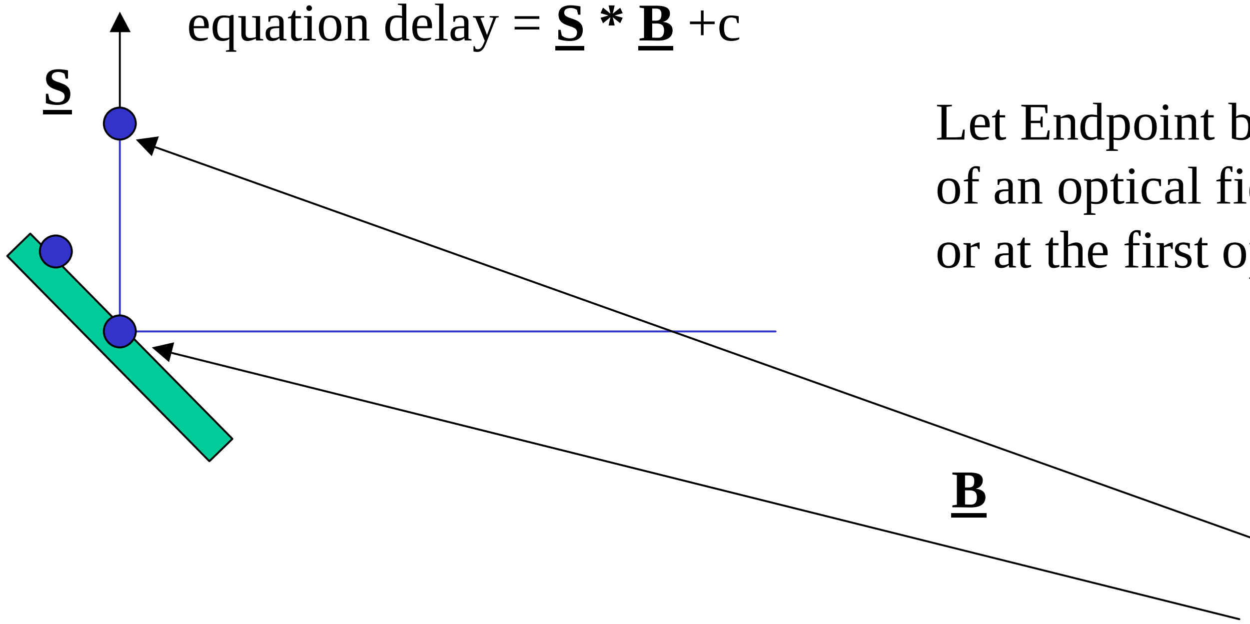
None of the above?

The ends of the baseline vector has to have 2 properties:

Defining the Baseline Vector

Property 1, the end points of the baseline vector must be measurable (with a laser metrology system)

Property 2, the definition of end point must satisfy the key equation delay = **S** * **B** +c

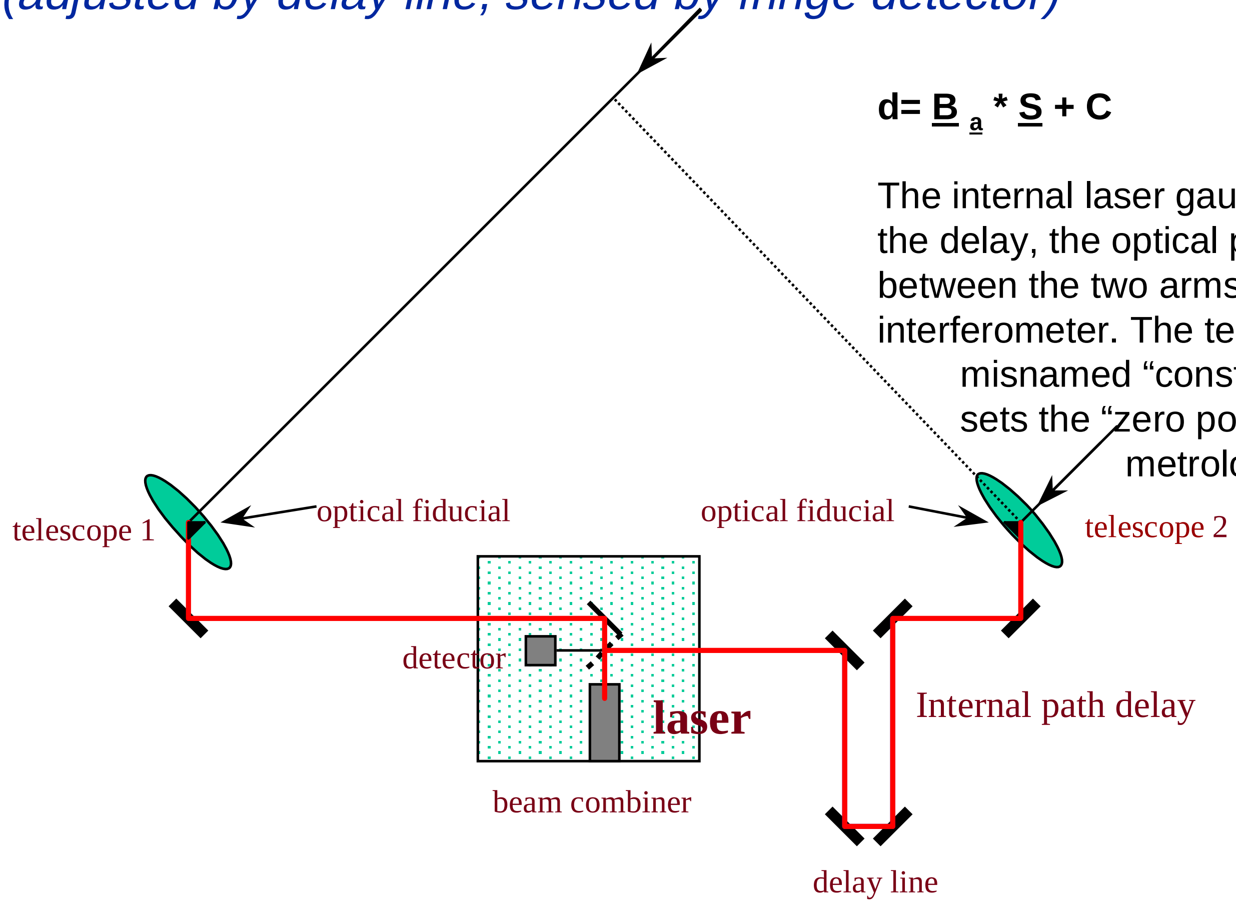


Let Endpoint be the location of an optical fiducial, before or at the first optic.

Measuring the Delay

Laser gauge measures internal delay

(adjusted by delay line, sensed by fringe detector)



d= $\underline{\mathbf{B}}_{\underline{a}}$ * $\underline{\mathbf{S}}$ + C

The internal laser gauge measures the delay, the optical path difference between the two arms of the interferometer. The term C is the misnamed “constant” term that sets the “zero point” of the metrology gauge.

Laser path retraces starlight path from combiner to telescopes

Monitoring B and C

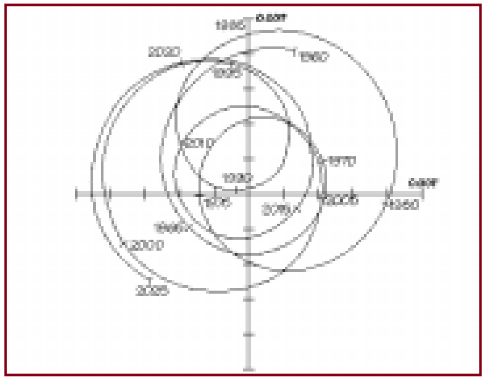
- In radio interferometry, the baseline is assumed fixed to the Earth (imperfect pivot axes, are modeled)
- At optical wavelengths, the imperfections are so large they have to be measured.
  - When an interferometer moves to point from star A to star B, all 4 instrument parameters <u>**B**</u>, **c** change
  - These changes must be measured to (100’s nm to 10’s pm)

Wide and Narrow Angle Astrometry

- Scientific objectives
  - Narrow angle examples
  - Wide angle examples
- Instrumental and observational differences
  - Why narrow angle?
    - Ground based
    - Space based
  - Reference frames
    - Inertial reference
    - Local reference

Astrometric Planet Detection

Planetary systems inducing only low radial velocities (<1m/s) in their central star and therefore, not possible to detect from the ground can be detected through the astrometric displacement of the parent star.



Reasons for astrometric searches

Unique mass, not Msin(I)

Down to 1/20 Mj mass (5AU)

100's of nearby stars

Inclination of orbital planes

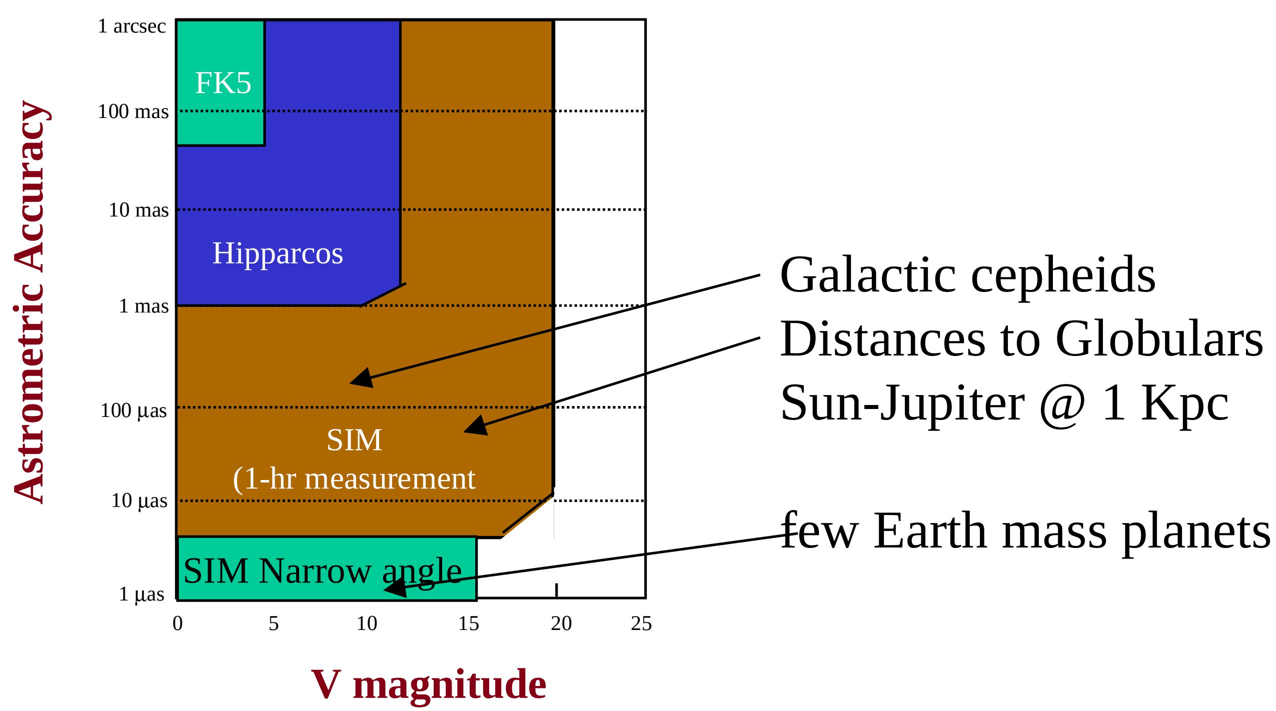
<u>Detection Limits</u>

SIM: 1 µas over 5 years (mission lifetime)

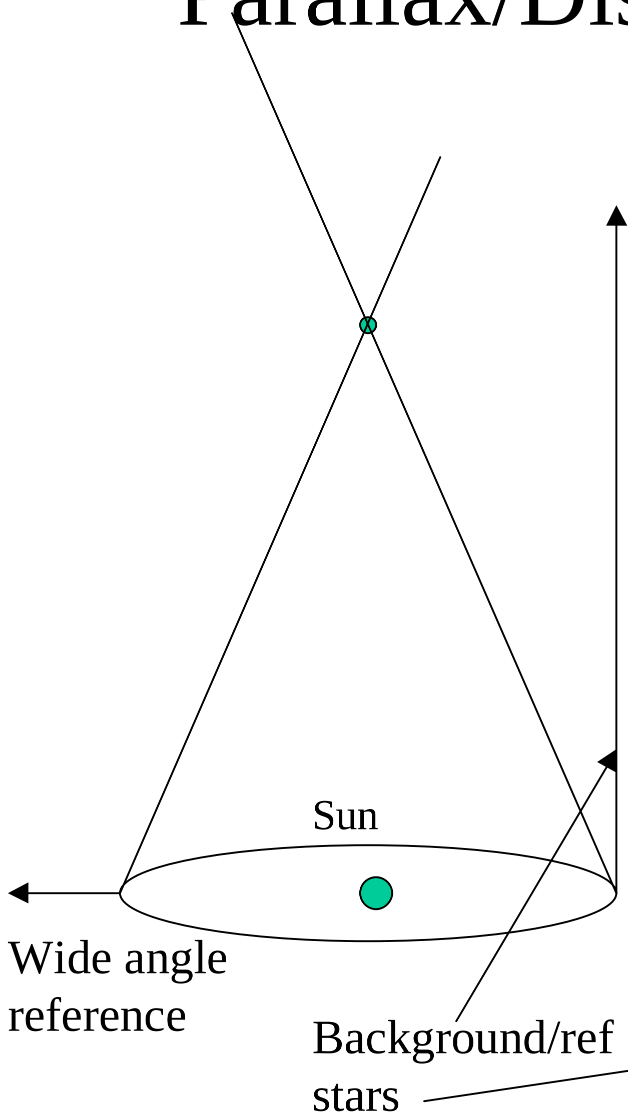
Keck Interferometer: 20 µas over 10 years

Science Objectives

- Planets (down to a few Earths)
- Cosmic Distance Scale (wide angle astrometry)
- Dark matter (Macho masses, galactic halo etc.)
- Galactic rotation/dynamics
- Stellar astrophysics



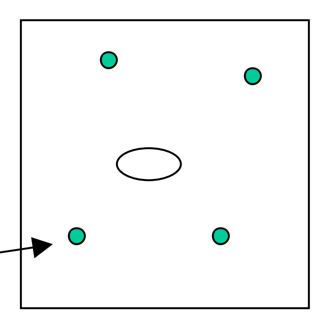
Parallax/Distance Measurements



Historically, parallax measurements were done with narrow angle astrometry

But at distances > 1kpc (1mas) distant ref stars cease to exist. (All bright stars in our galaxy are within 1~2 kpc of the Sun.

Starting with Hipparcos, parallax measurement became “global” astrometry. By using a ref star 90 deg away, the parallax effect of the ref star is zero.

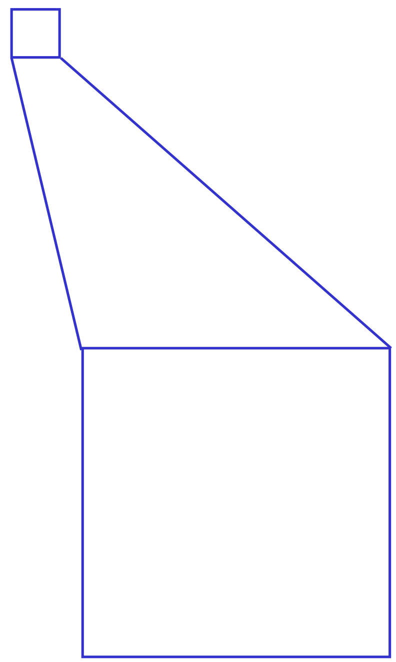


Global and Narrow angle Astrometry

Globular Clusters are an example of both Global and Narrow angle astrometry (and imaging)

HST-WFPC2

Cluster Core Model



Resolution 53 milliarcsec

"True star positions"

SIM

Narrow angle
to measure motions
within the cluster

Global to measure
parallax and motion
of the cluster around
galaxy

Resolution 10 milliarcsec
Field of View 0.3 arcsec

Instrumental Differences (wide/narrow)

- Why narrow angle?
  - Many instrumental errors in astrometric interferometry are angle dependent. In general narrow angle astrometry will be more accurate than global astrometry
- What type of error get small with smaller fields of view?
  - Differential astrometry (with interferometers)
  - delay = S * B + C

    δ delay = $(\underline{\mathbf{S}}_1 - \underline{\mathbf{S}}_2) * \underline{\mathbf{B}}$
  - If we want to measure the angle between stars 1,2, and we measure δ delay with a certain accuracy ε and B with a certain accuracy the accuracy of $(\underline{\mathbf{S}}_1 - \underline{\mathbf{S}}_2)$ is

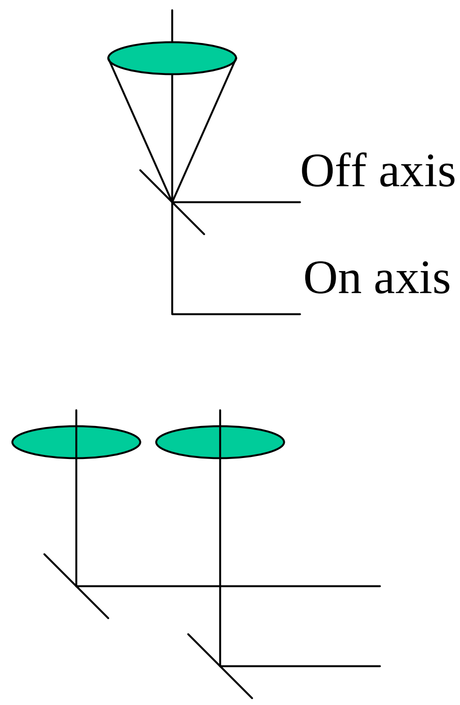
    $\Delta(\underline{\mathbf{S}}_1 - \underline{\mathbf{S}}_2) = \Delta\mathbf{(}\delta \text{ delay}\mathbf{)}/B - \Delta B^* (\delta \text{ delay})/B^2$
  - Errors in measuring the baseline matter less for narrow angle astrometry

Higher Accuracy at Small Angles

- The atmosphere is better behaved at small angles. In a differential measurement the light from two nearby stars tend to go through the same atmosphere.
- At sub-nm levels (for space) a huge number of errors grow linearly with the field of view.
  - Delay line metrology errors
  - Optical fiducial errors
  - V/C correction (stellar aberration)

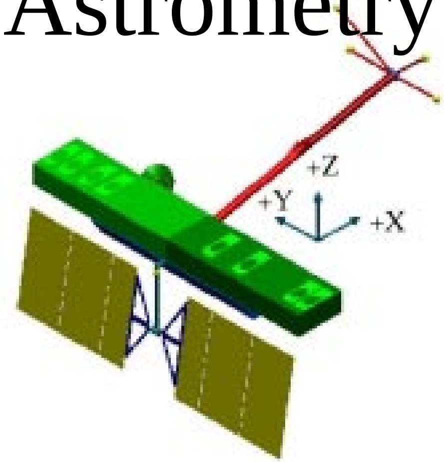
Optical Architectures for Narrow Angle Astrometry

- Two approaches to narrow angle astrometry
  - Keck dual star approach
  - SIM separate interferometer
- Narrow angle offers a potentially different architecture by using the same telescope to look at several stars at the same time.
- This approach is best for the ground where large apertures are available, and off axis errors of the optics aren't important



Ground and Space Astrometry

Baseline fixed to the Earth
Earth rotation rate very stable
(if modeled)
Baseline orientation is known to
~100 uas (VLBI) ~mas (optical)
Turbulent atmosphere major
error source

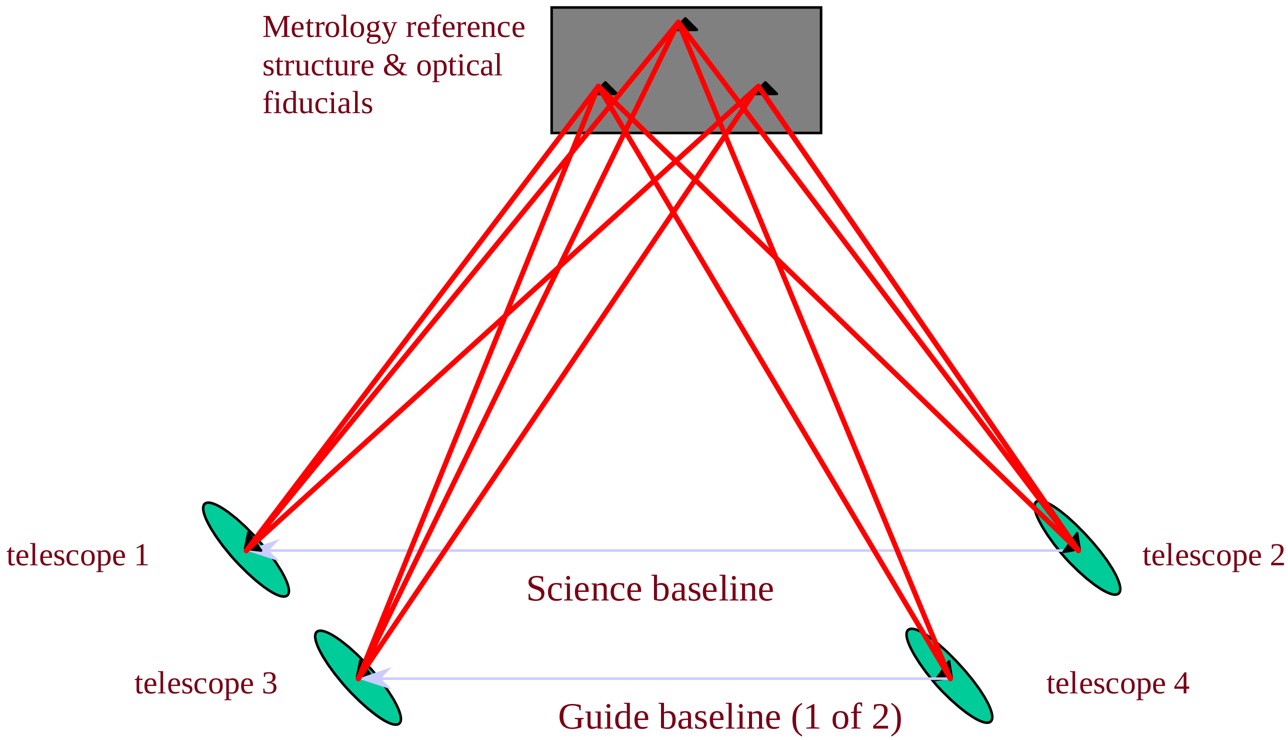


Spacecraft orientation is not stable. (gravity gradients, solar radiation pressure)

The Baseline orientation has to be measured, by **“guide interferometers”**

Star trackers provide attitude information
to a few arcsec accuracy
Guide interferometers provide attitude or
baseline orientation to a few uas.

SIM external metrology



The external metrology system provides the relative orientations and lengths of the interferometer baselines

Technical Challenges/Limits
Ground vs Space

- Ground based
  - limited by the atmosphere
    - few mas (global)
    - 10~20 uas narrow
- Space
  - Extremely accurate metrology
  - Extreme thermal stability
  - High cost

- Ground based
  - Long baselines
  - Lower cost
- Space based
  - Not limited by atmosphere
  - High accuracy fast (30sec vs 1 hr)
  - uas global astrometry
  - Only way to get Earths (astrometrically)